The ALICE physics program

Incontri di Fisica delle Alte Energie
Torino, April 14-16 2004

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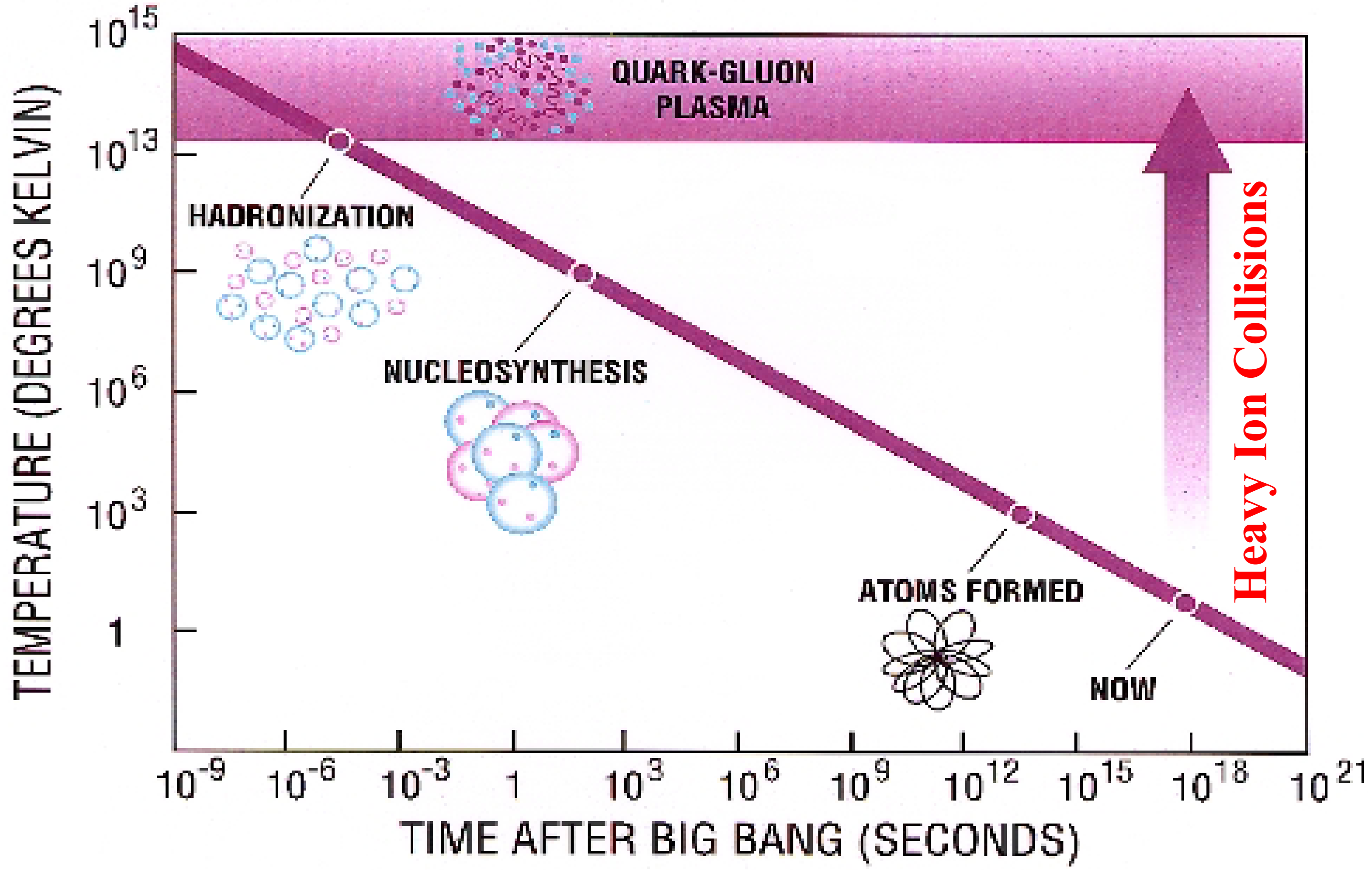
for the ALICE Collaboration

- Introduction on Quark-Gluon Plasma physics
- ALICE, the dedicated heavy-ion experiment at the LHC
- Physics observables in ALICE

Why do we study QGP ?



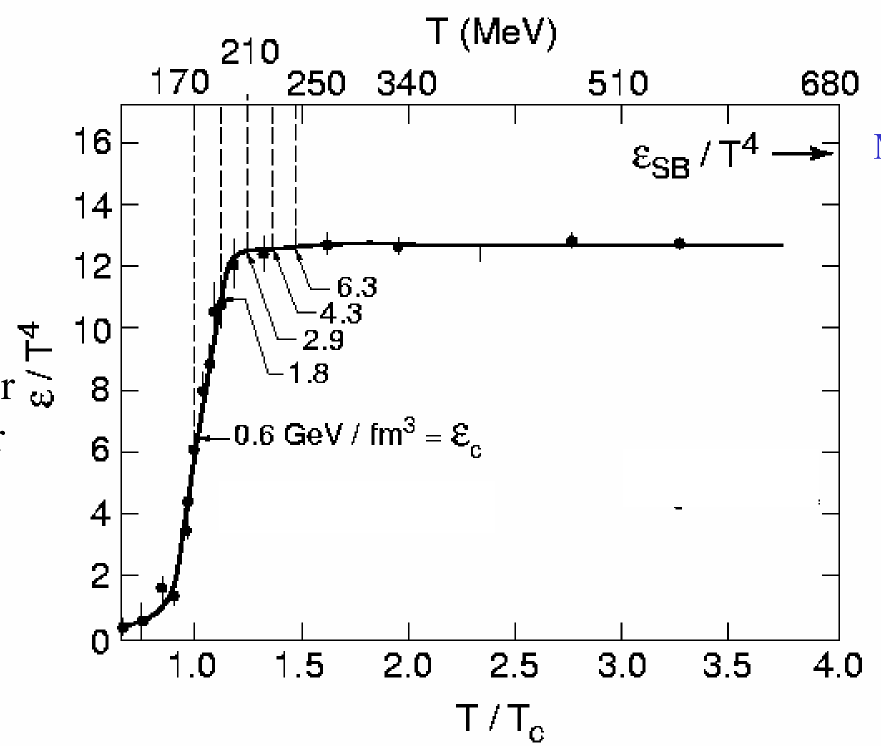
- Recreate the early stage of the universe, breaking in the lab the links that bind some quarks inside nucleons since the Big Bang
- Investigate the limits of hadronic confinement
- Study the role of chiral symmetry in the generation of hadron masses

Lattice calculations

- Lattice QCD calculations:
  - Confirm the existence of a phase transition from a hadronic gas to a deconfined state of quarks and gluons, the QGP
  - Predict numerical values for T_c and ε_c
  - Predict that above T_c chiral symmetry should be restored (quark masses are reduced from their large effective values to small bare ones)

$T_c = (175 \pm 15)$ MeV

- Order of the phase transition critically depends on quark masses
- 2 flavors, zero mass →2nd order
- 3 flavors, zero mass →1st order



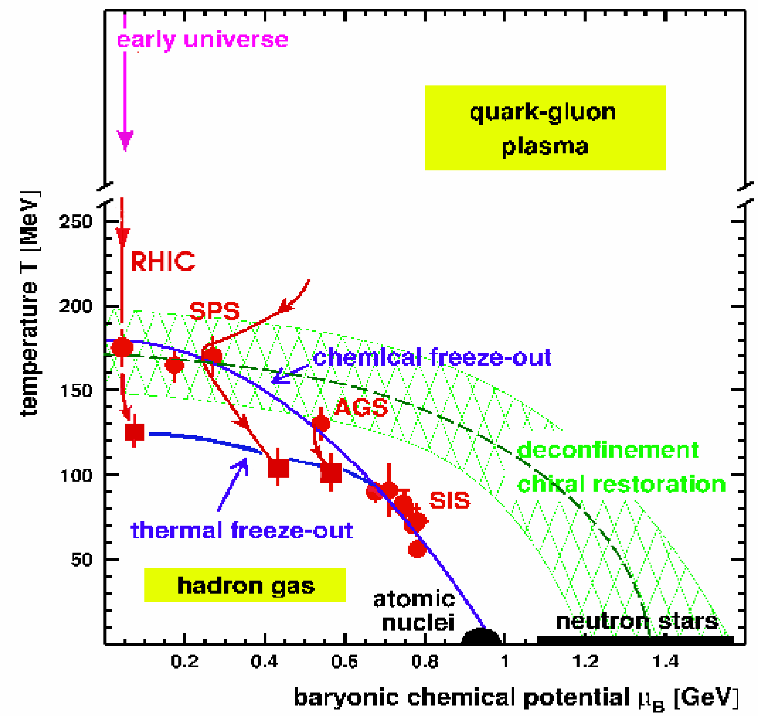
Miss the Stefan-Boltzmann regime

- Residual interactions still present
- Not an "ideal" plasma

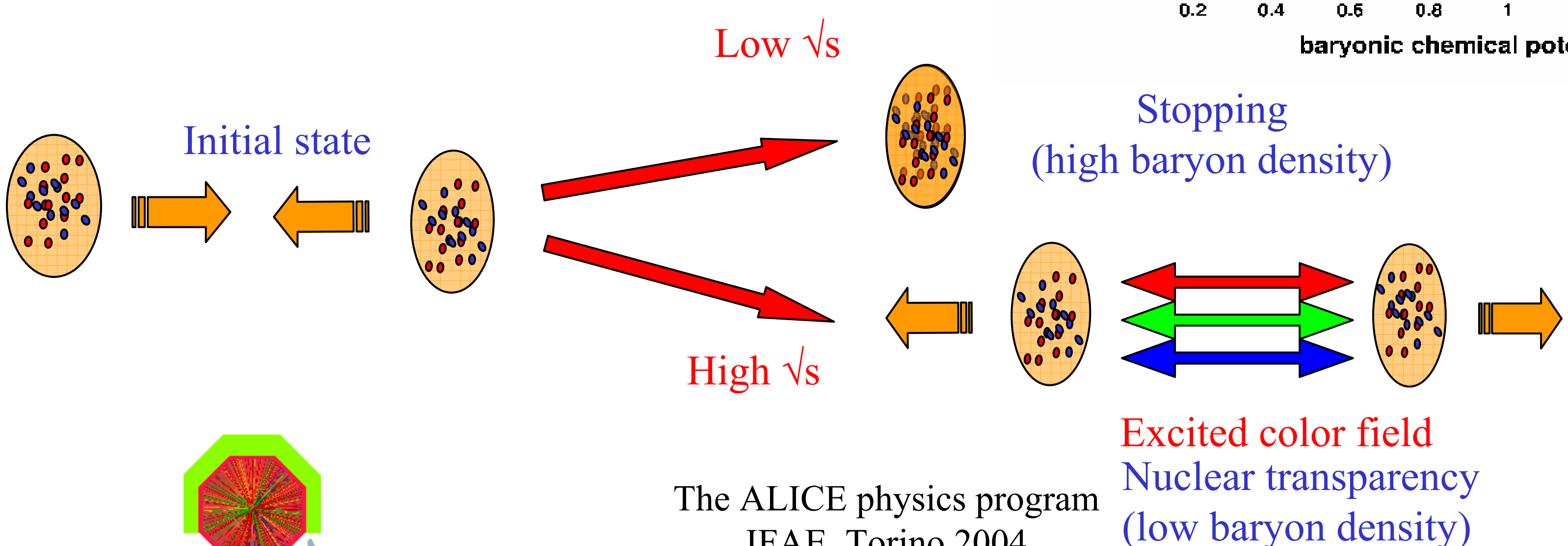
F. Karsch, Nucl. Phys. A698(2002) 199c

Phase diagram of strongly interacting matter

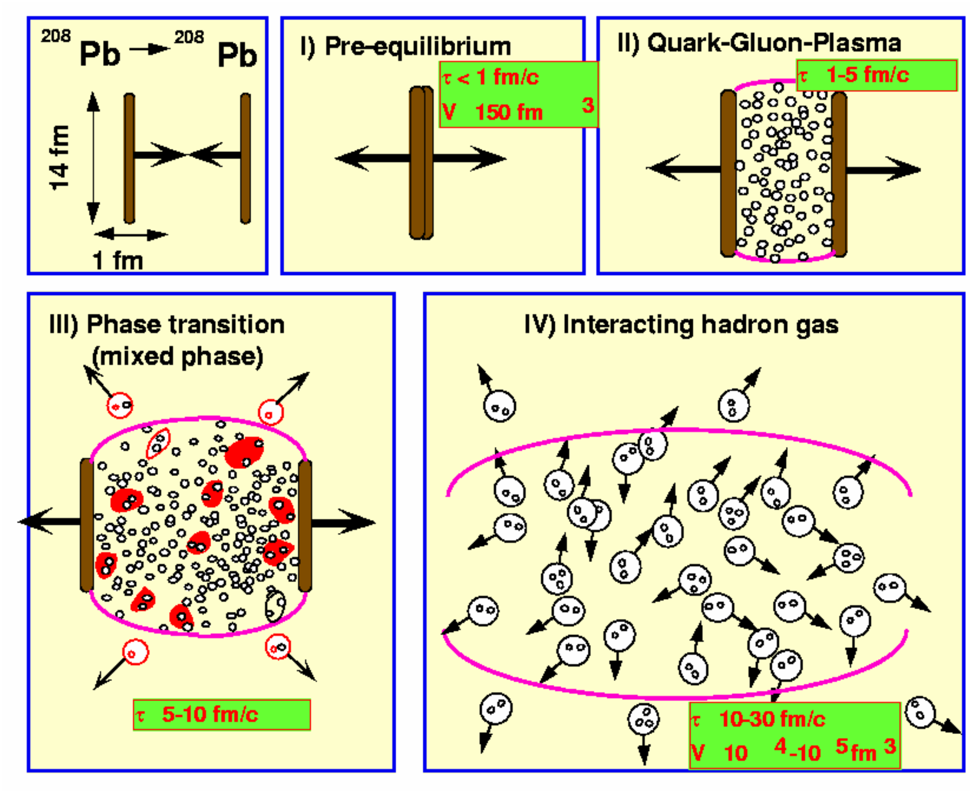
•Can we go from the normal hadronic matter to the QGP phase by doing high energy heavy ion collisions in the lab ?



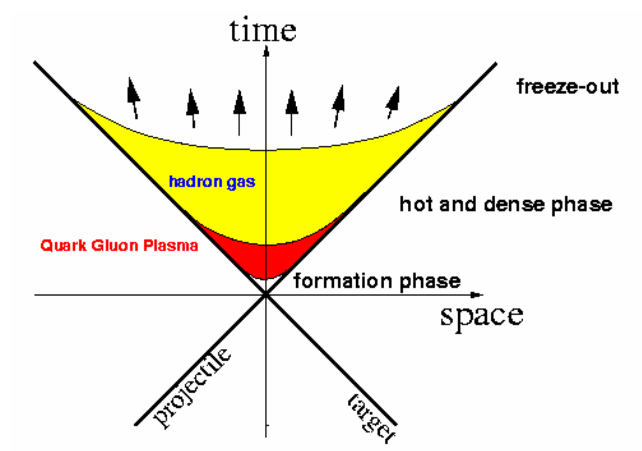
•In order to reach the very high energy density required (~1 GeV/fm^3), large amounts of energy must be released in a small (but not too small) region of space in a short duration of time



Time evolution of heavy ion collisions

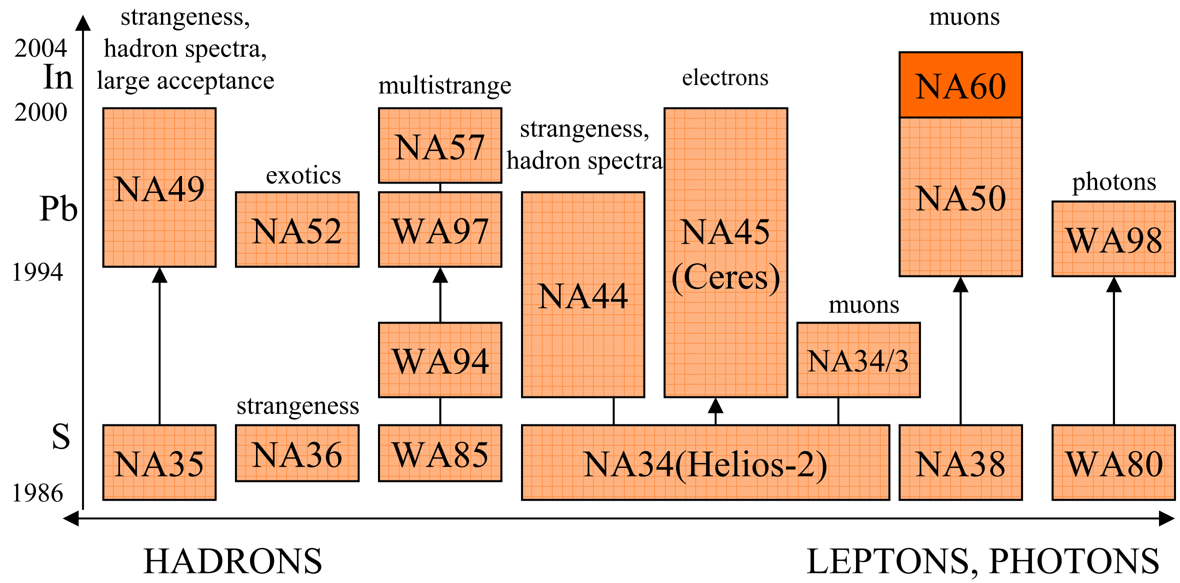


- Initial conditions
  - Target/projectile mass
  - Energy
  - Impact parameter
- Pre-equilibrium
  - Hard interactions
    - Jets, heavy quarks, J/ψ
- Quark-gluon plasma
  - Thermal system of partons
- Phase transition
  - Formation of hadrons
- Hadron gas
  - Interacting hadronic matter

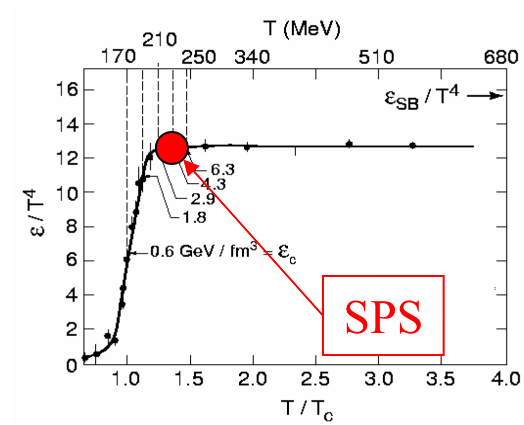


- Final state particles fly to our detector
→we have to infer from them details of the collision history
- There is no "fundamental theory" which directly explains the rich phenomenology observed in heavy ion collision
- History has taught us that this is largely a **data driven field**

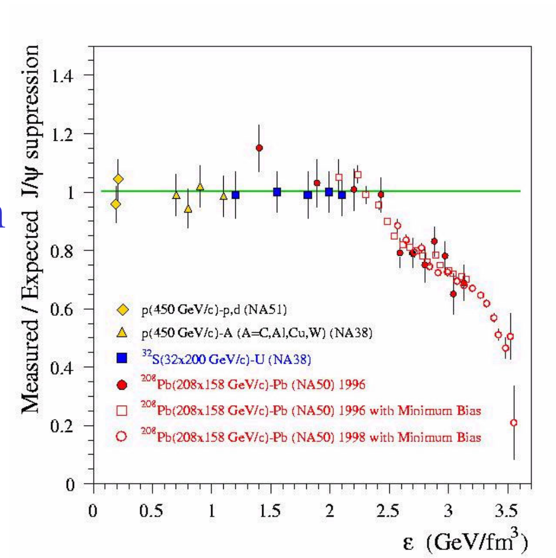
Before the LHC: SPS

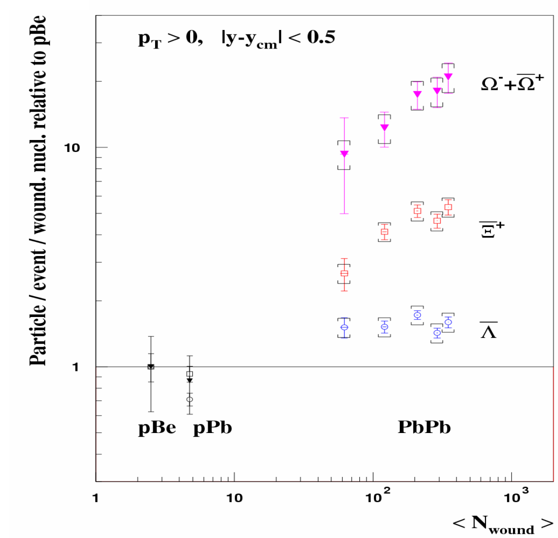


- Energy density high enough to detect effects due to deconfinement



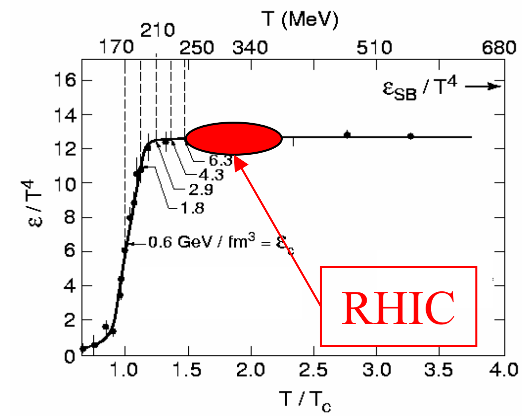
- Most striking observations:
  - Anomalous J/ψ suppression (NA38/NA50/NA60)
  - Strangeness enhancement (WA97/NA57) (with respect to pA)



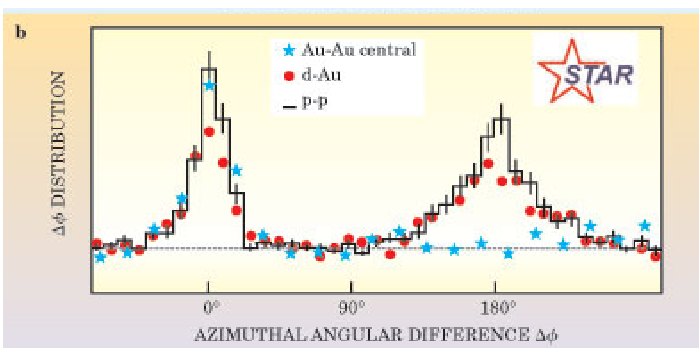


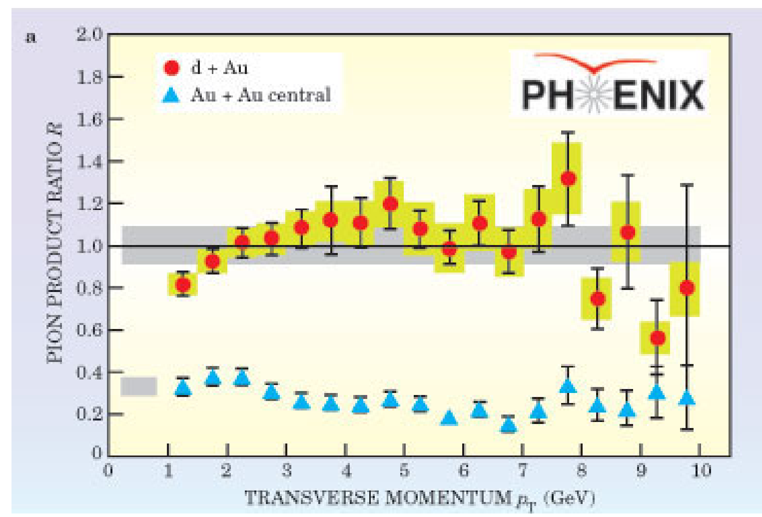
Before the LHC: RHIC

- Jump in √s by ~ one order of magnitude
- From √s ~ 20 AGeV to √s = 200 AGeV



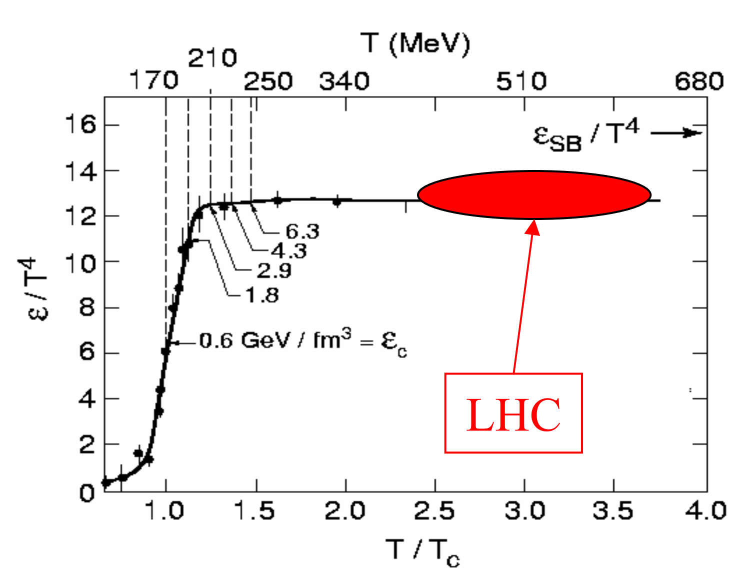
- Most striking observation (up to now)→ jet quenching

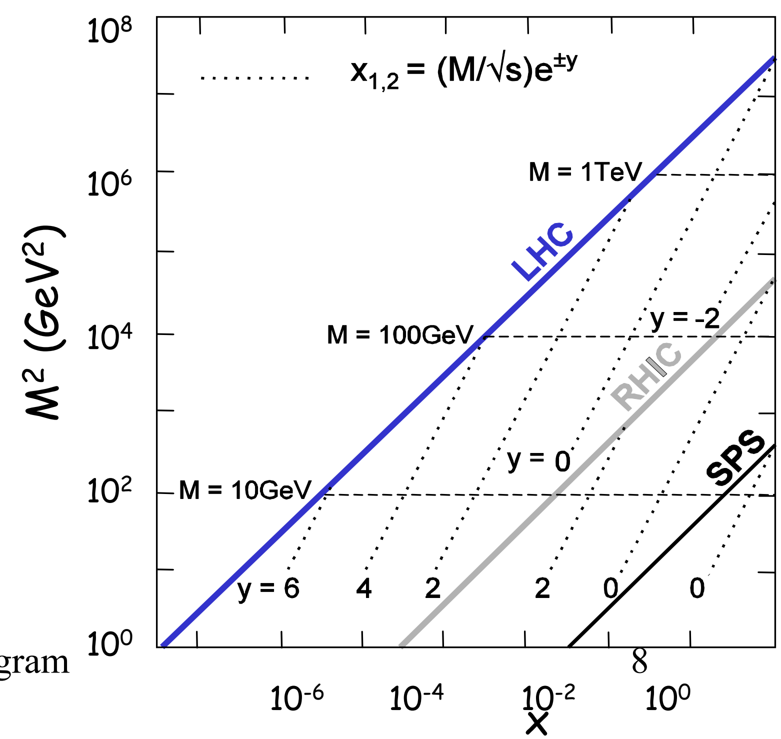




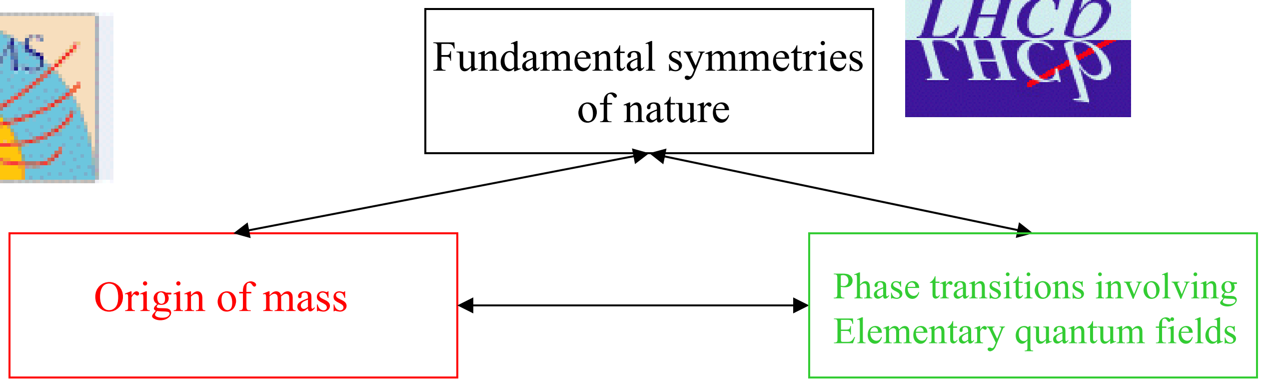
Why heavy ions at the LHC ?

- Access a new energy regime
  - Quantitatively
    - Factor 30 in √s with respect to RHIC
    - Much higher energy density
  - Qualitatively
    - High density parton distributions determine particle production
    - Hard processes contribute significantly to the total A-A cross section
    - Weakly interacting hard probes become accessible
    - Parton dynamics dominate the fireball expansion



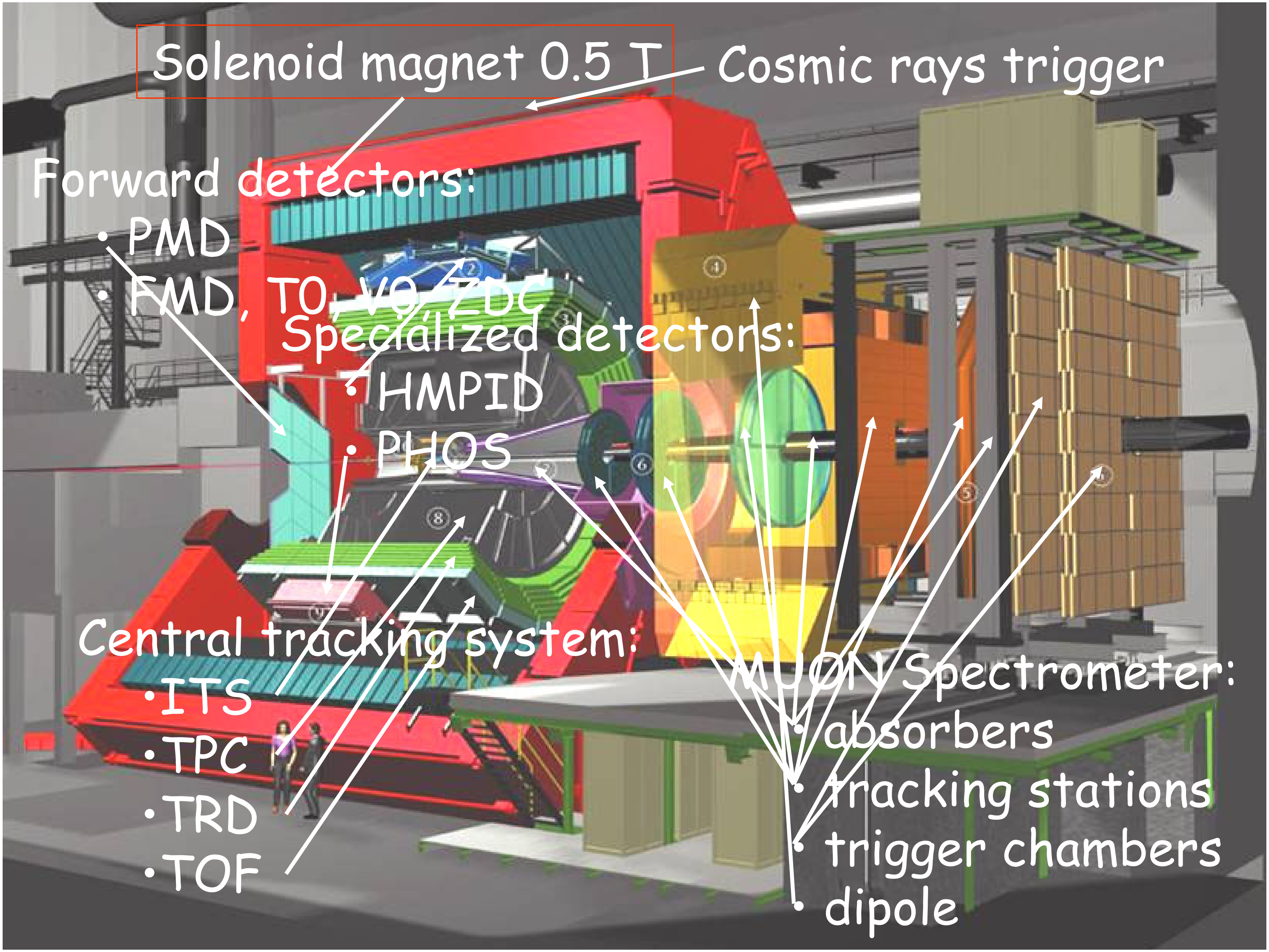


ALICE and the LHC program



LHC $\rightarrow$ explore various aspects of the symmetry breaking mechanisms through complementary experimental approaches

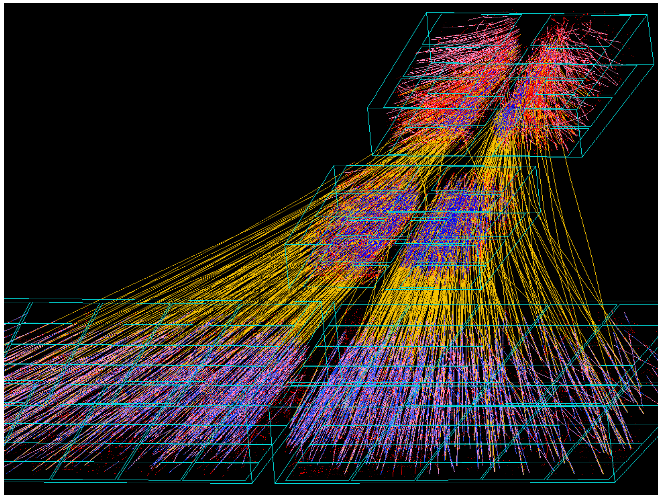
- CMS, ATLAS
  - Higgs particle, spontaneous breaking of the electroweak gauge symmetry
- LHCb
  - CP symmetry-violating processes, misalignment between gauge and mass eigenstates
- ALICE
  - Role of chiral symmetry in the generation of mass in composite hadrons, (non)equilibrium physics of strongly interacting matter in the range $1 < \varepsilon < 1000$ GeV/fm^3


Solenoid magnet 0.5 T
Cosmic rays trigger
Forward detectors:
• PMD
• FMD, T0, V0, ZDC
Specialized detectors:
• HMPID
• PHOS
Central tracking system:
•ITS
•TPC
•TRD
•TOF
MUON Spectrometer:
• absorbers
• tracking stations
• trigger chambers
• dipole

ALICE: the dedicated HI experiment at the LHC

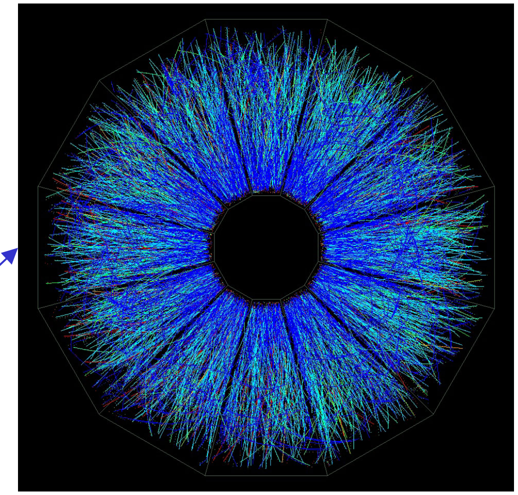
- Measure flavor content and phase-space distribution event- by-event:
  - Most (2π * 1.8 units η) of the hadrons (dE/dx + ToF) , electrons (dE/dx, transition radiation, magnetic analysis) and photons (high resolution EM calorimetry)
  - Track and identify from very low (< 100 MeV/c; soft processes) up to very high p_T (~100 GeV/c; hard processes)
  - Identify short lived particles (hyperons, D/B meson) through secondary vertex detection
  - Muons in the forward region ($2.5 < \eta < 4.0$), in a wide p_T range (hadron absorber + magnetic spectrometer)
  - Jet identification

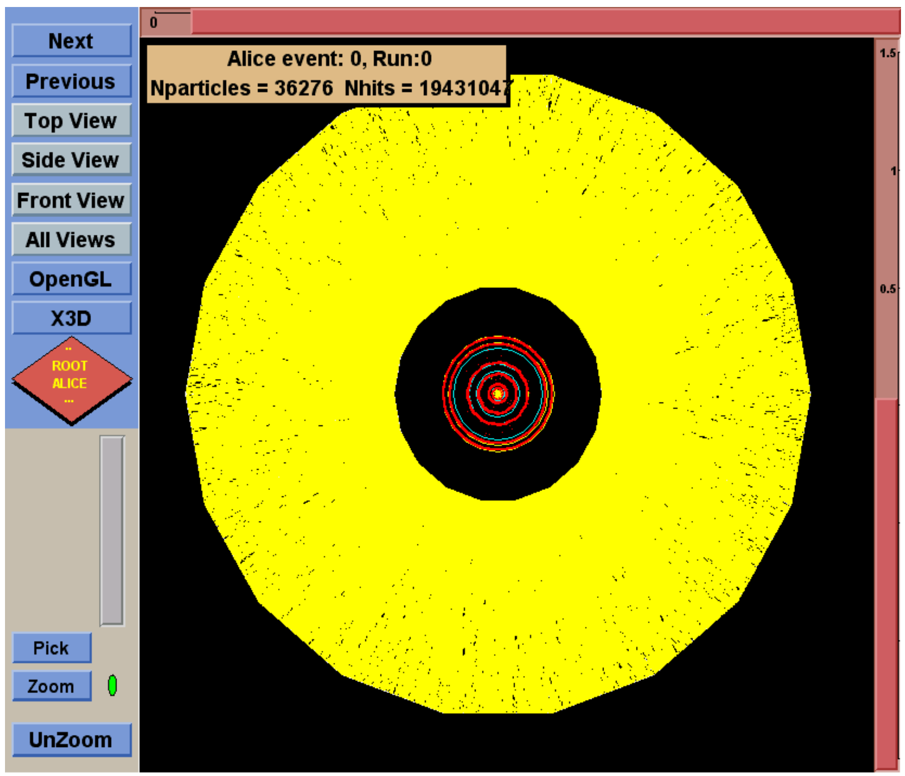
The experimental challenge



SPS
dN/dη (Pb-Pb) ~ 4·10²

RHIC
dN/dη (Au-Au) ~ 7·10²





ALICE
Optimized @ dN_{ch}/dy=4000,
Checked up to 8000

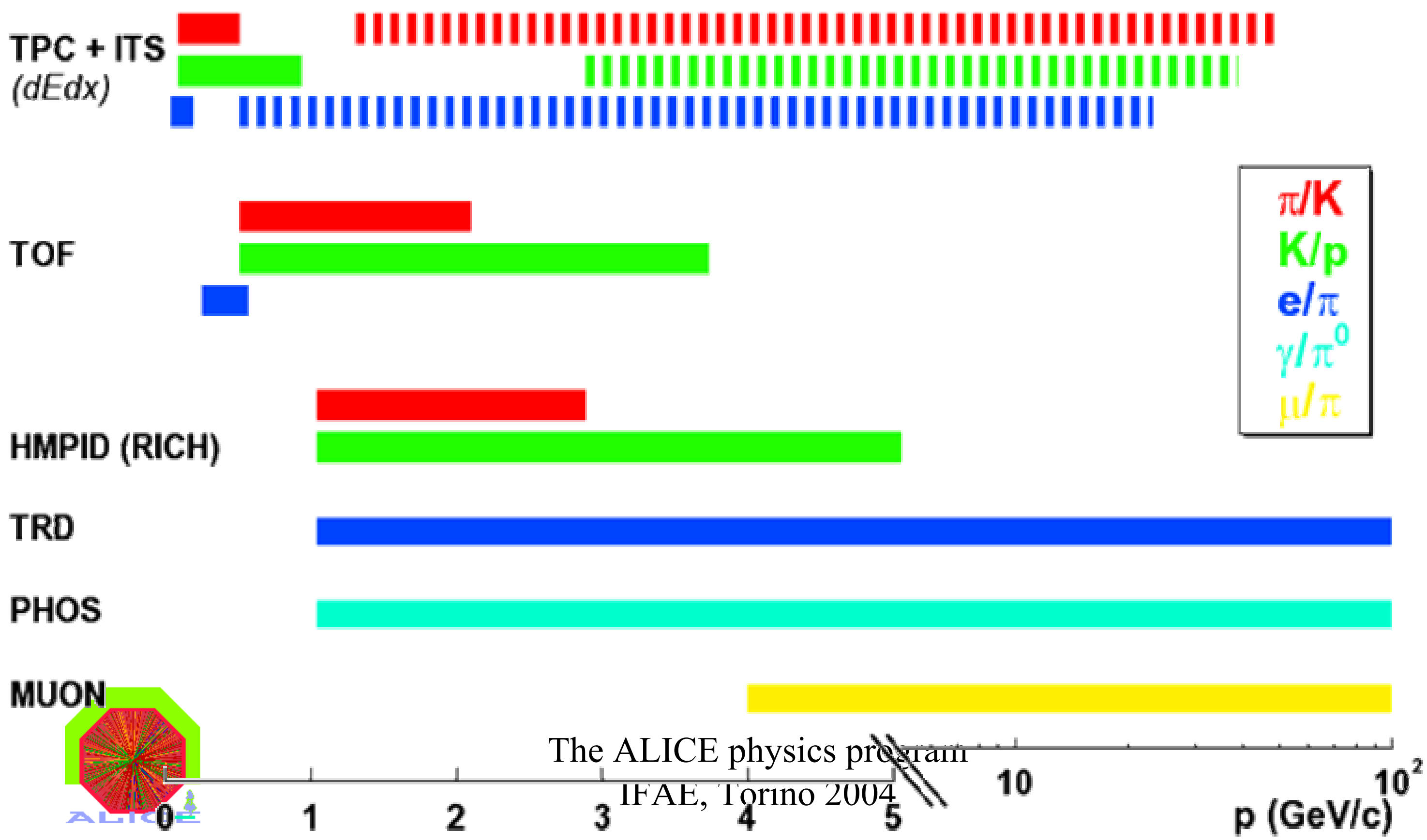
Performances: PID

• π, K, p identified in large acceptance (2π * 1.8 units η) via a combination of dE/dx in Si and TPC and TOF from ~100 MeV to 2 (π/K) - 3.5 (K/p) GeV/c

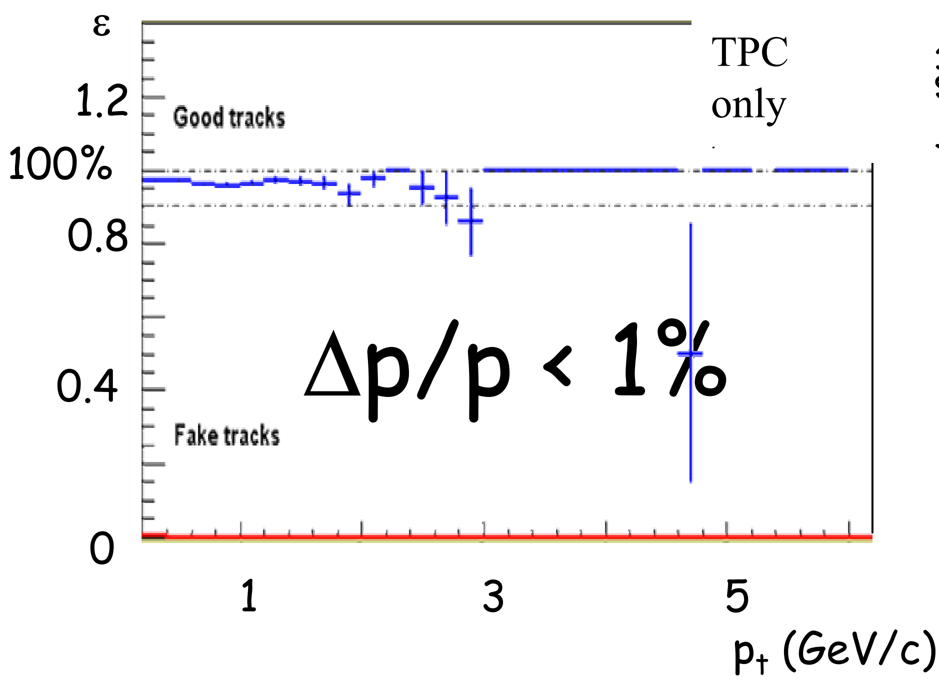
•Electrons identified from 100 MeV/c to 100 GeV/c (with varying efficiency) combining Si+TPC+TOF with a dedicated TRD

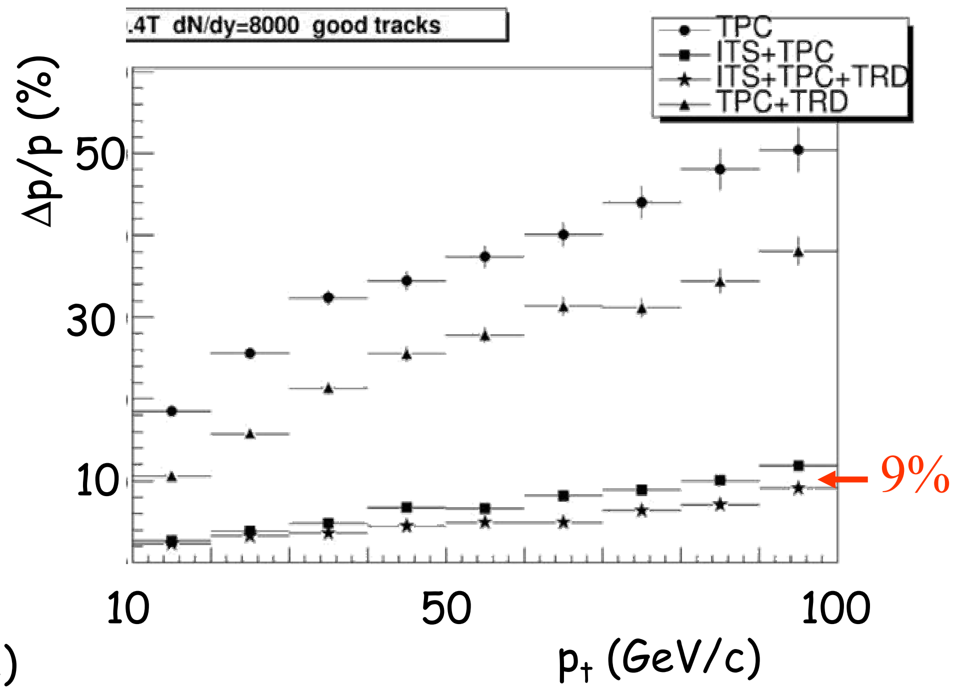
•In small acceptance HMPID extends PID to ~5 GeV

•Photons measured with high resolution in PHOS, counting in PMD



Performances: tracking efficiency and momentum resolution





Diagnostic tools

•The experimental challenge:

•observe in the final state the signatures of the phase transition

•get information on the deconfined state

Caveat: pure hadronic effects can mimic expected QGP signaturures

Therefore one needs:

• to establish experimentally a **solid baseline** studying systems where no QGP is expected (e.g. **pp, pA**) and use these data as a reference

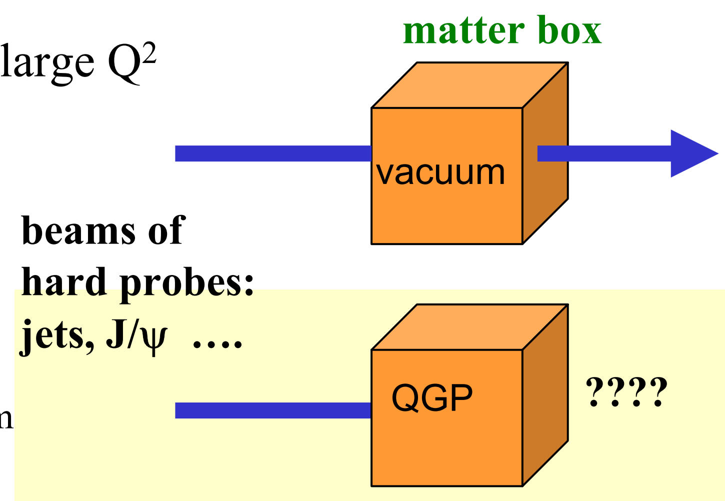
• Low-p_t "soft" probes

- single particle spectra
- two particle correlations
- particle abundances and ratios
- flow patterns

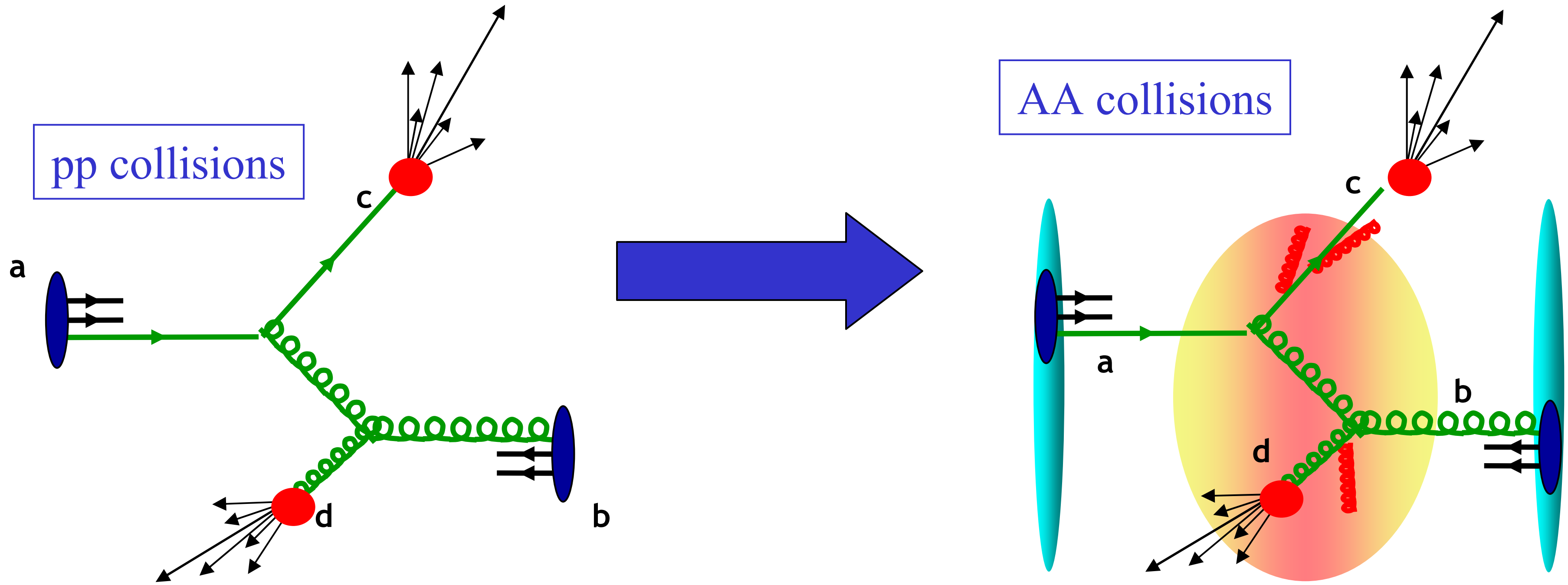
•**thermal** particle production from QGP (photons, dileptons)

• High-p_t "hard" probes

During formation phase parton scattering processes with large Q^2 create high mass or high momentum objects that penetrate hot and dense matter and are sensitive to the nature of the medium



Hard probes: parton energy loss



• Large p_T partons are produced very early in heavy-ion collisions

• Production rates can be calibrated in pp and pA collisions @ the same energy.

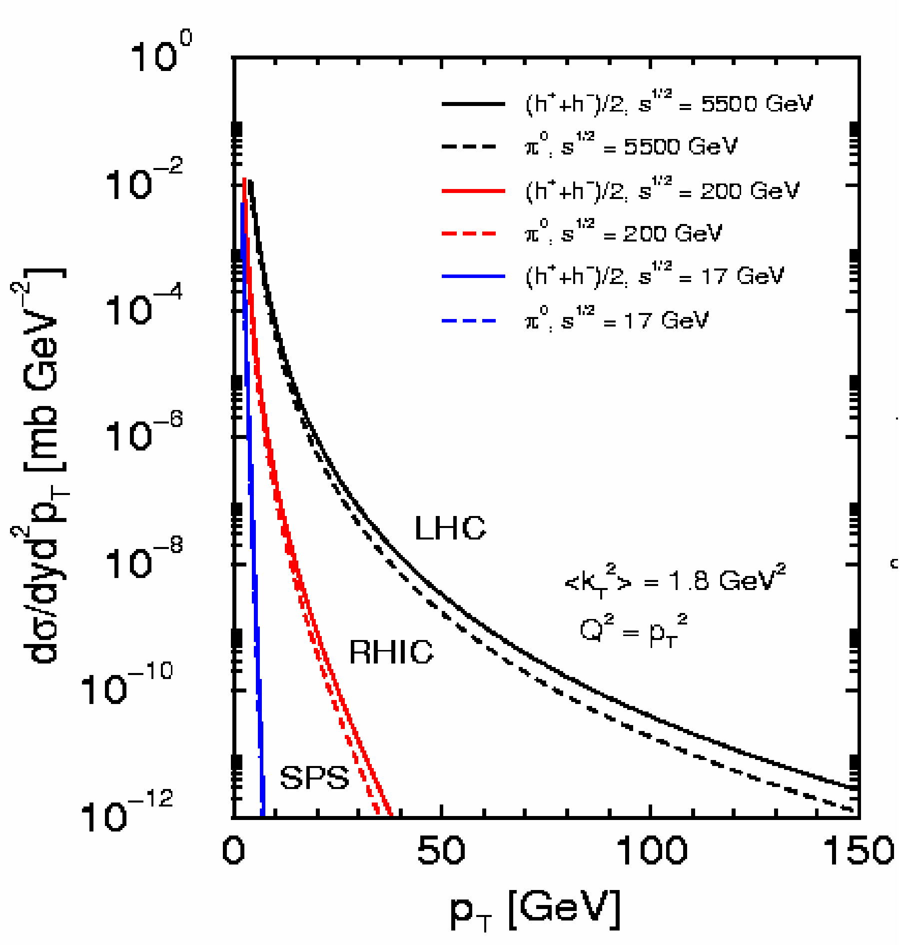
$\Rightarrow$ ideal probes of the dense matter that is formed in the same reaction

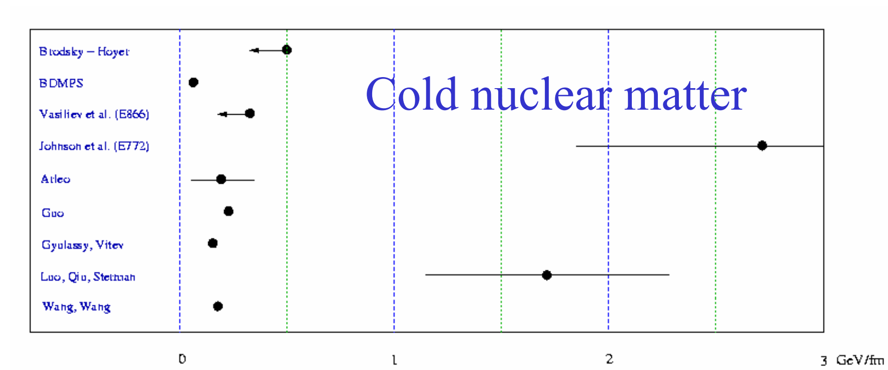
As the parton propagates through the matter

$\Rightarrow$ scattering induced energy loss

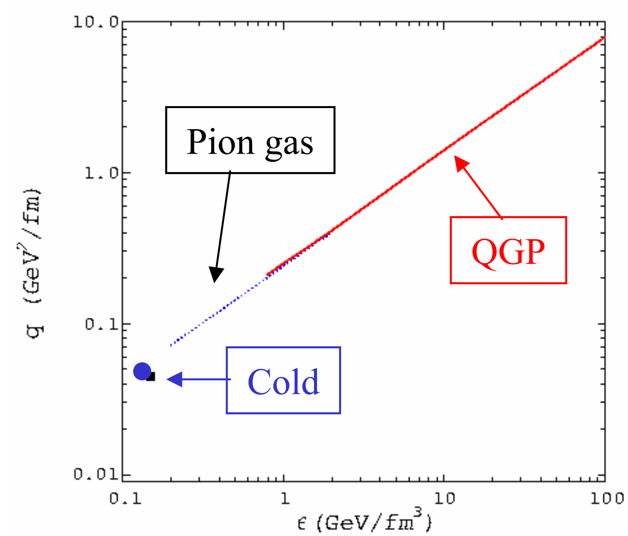
The parton energy loss is directly related to the parton density of the medium.

High p_T physics in ALICE



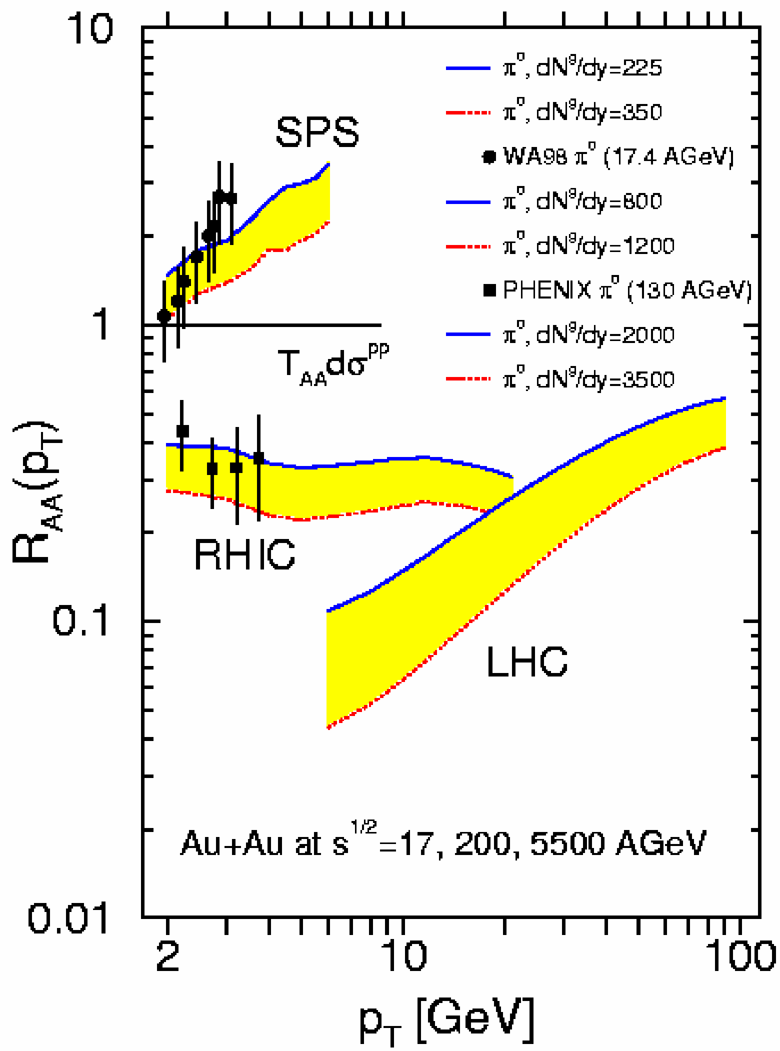


Observable very sensitive to the energy density of the medium (not to its deconfined nature)



- Statistics is not a problem
- Expected ~ 10^6 jets with $E_T > 100$ GeV (1 month running PbPb @ $L = 5\times10^{26}$ cm^{-2} s^{-1})

Leading hadron quenching @ LHC energy



- Stronger p_T dependence wrt RHIC
- SPS → Cronin effect
- RHIC → interplay of shadowing, Cronin effect and parton energy loss
- LHC → hardening of p_T spectra not balanced by Cronin effect

$$R_{AA} = \frac{1}{N_{coll}} \times \frac{dN_{AA}/dp_t}{dN_{pp}/dp_t}$$

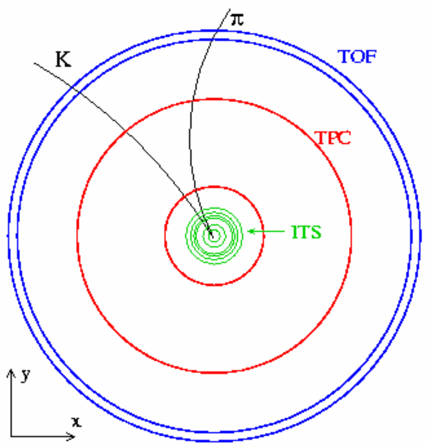
- Various experimental possibilities (require high quality tracking down to low p_t)
  - Reduction in the yield of high p_T particles
  - Particle ratios at high p_T
  - Dependence on nuclear geometry
  - p_T broadening of jet phenomena
    - Total energy inside cone
    - k_T broadening inside jet
  - Energy imbalance in dijet events

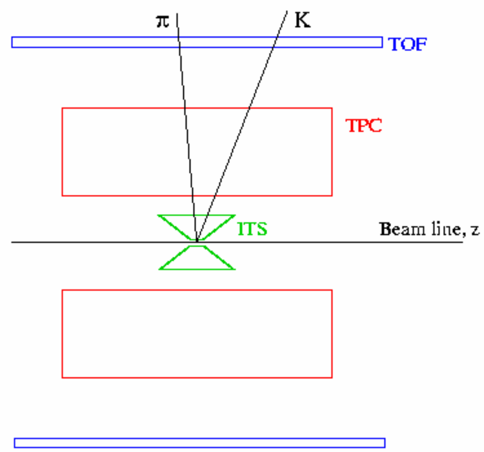
Charm production: detection

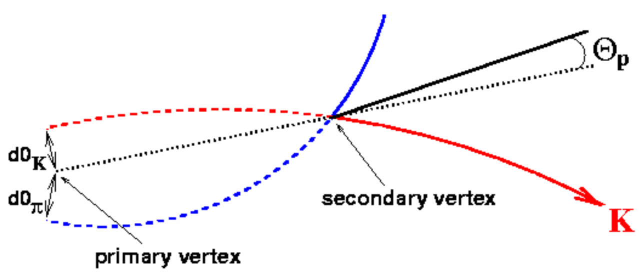
•Heavy quark production occurs at early stages $\rightarrow$ another probe of the medium

•Copious production

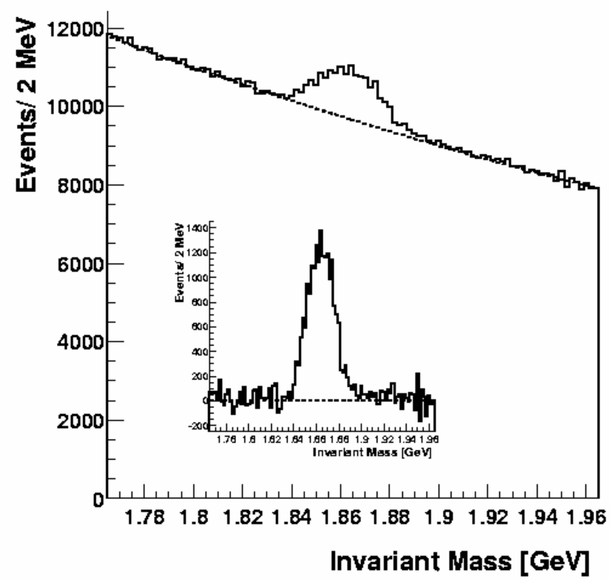
		σ_{pp} (mb)	
$\sqrt{s}$ (TeV)	$Q\overline{Q}$	MRST	CTEQ5M1
5.5	$c\bar{c}$	5.86	7.42
	$b\bar{b}$	0.19	0.22
14	$c\bar{c}$	10.28	12.07
	$b\bar{b}$	0.46	0.55







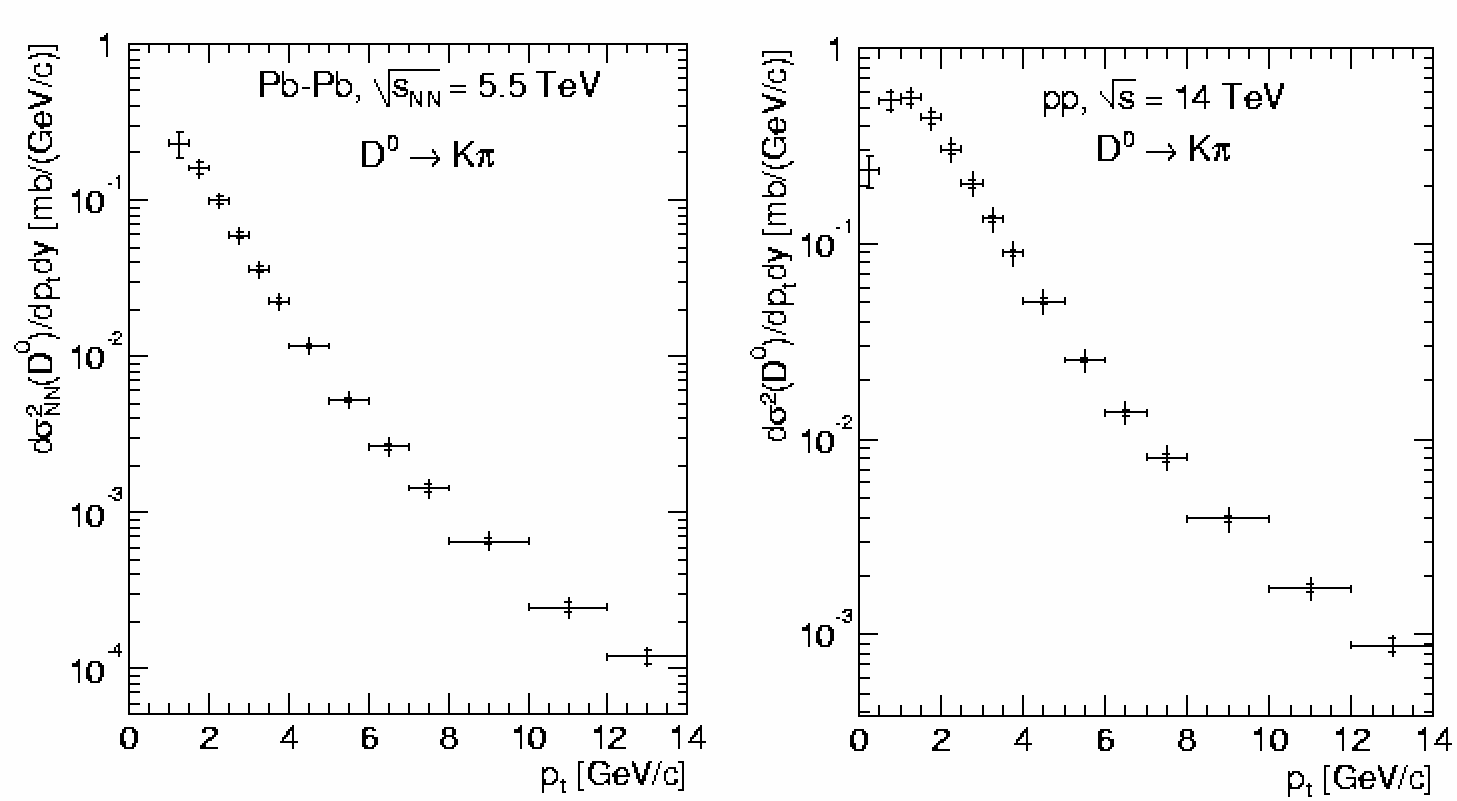
$c\tau = 124\ \mu m$



10^7 central PbPb events

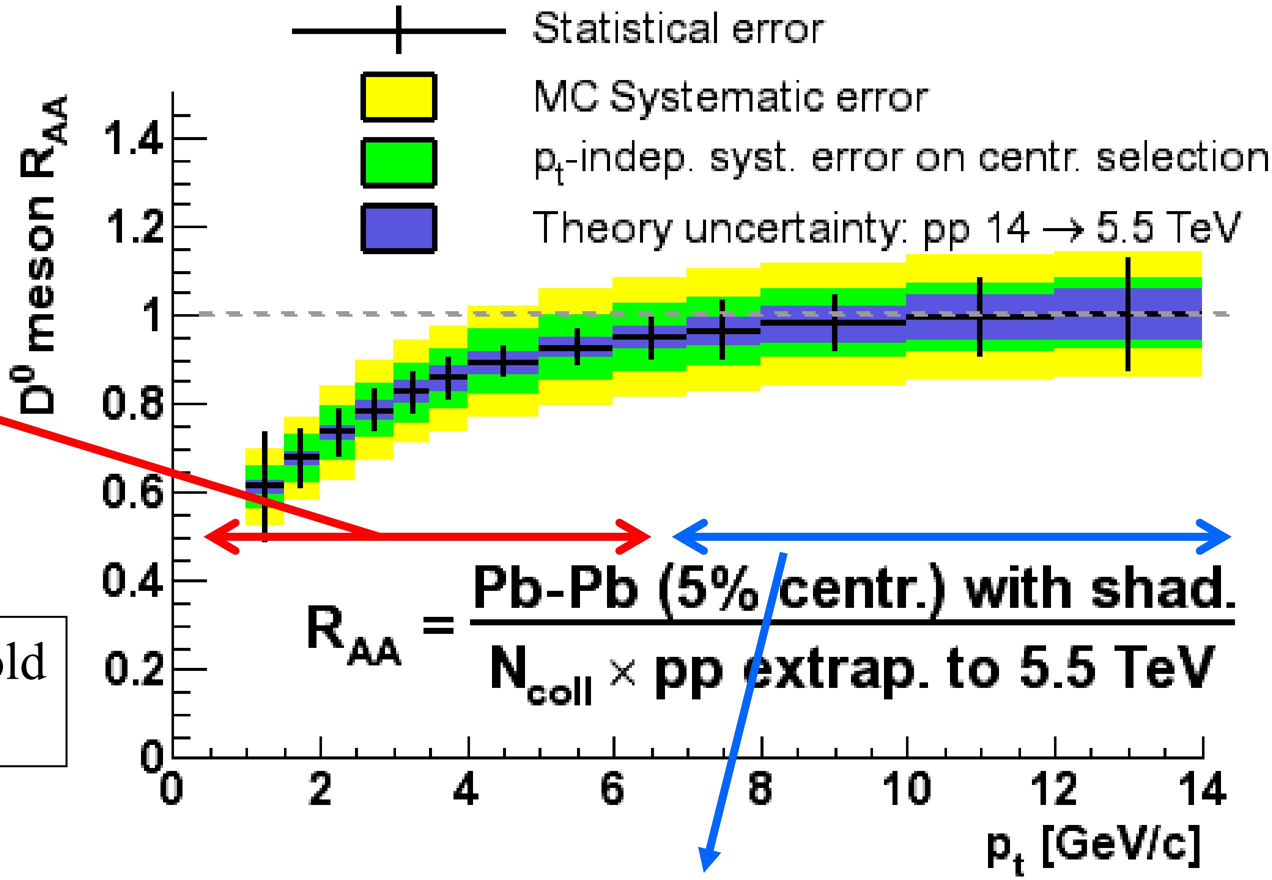
Charm production: yields in ALICE

system ($\sqrt{s}$)	S/event	B/event	S/B (%)	$S/\sqrt{S+B}$
Pb+Pb (5.5 TeV)	1.3×10^{-3}	1.2×10^{-2}	11	37 (10^7 events)
pp (14 TeV)	1.9×10^{-5}	1.7×10^{-4}	11	44 (10^9 events)



Charm in-medium quenching

Low p_t (< 6-7 GeV/c)
Nuclear shadowing



x-values @ threshold and midrapidity

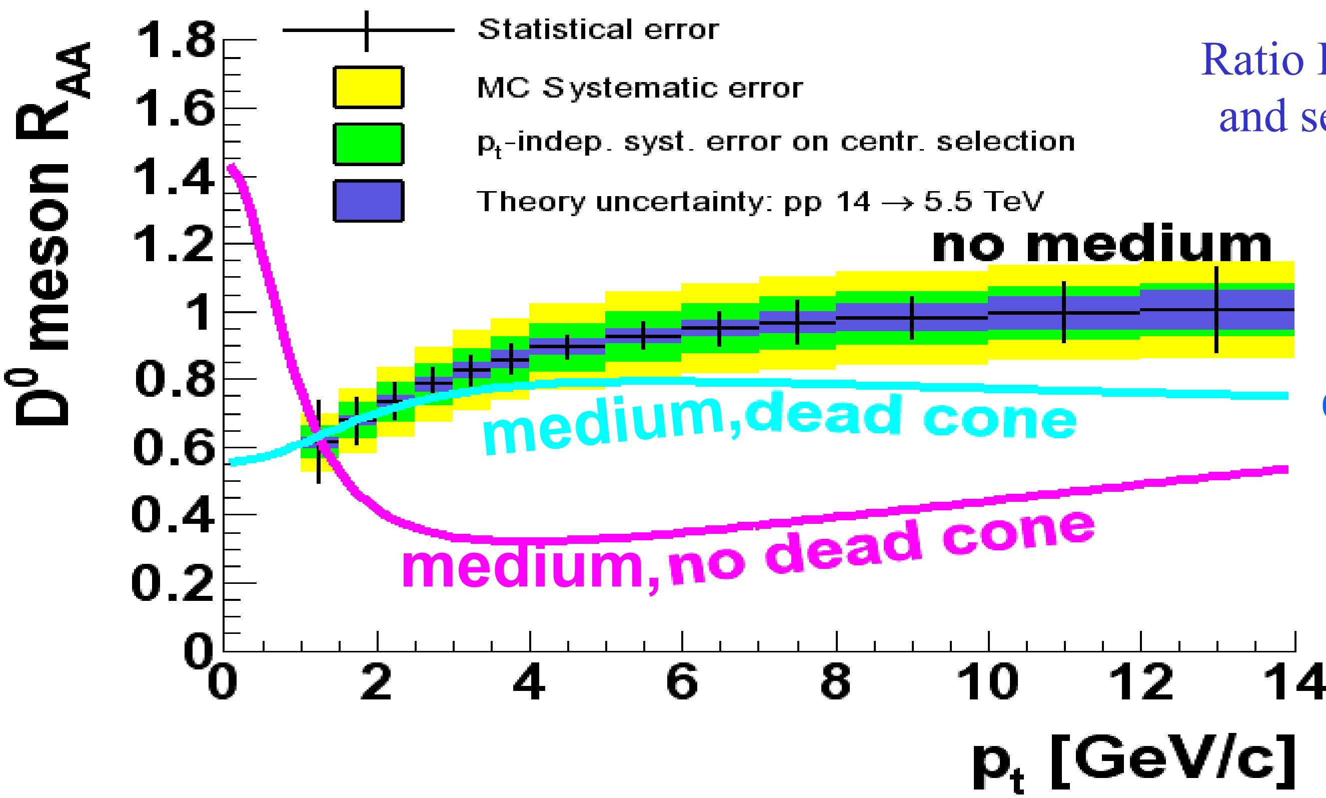
system ($\sqrt{s}$)	x ($c\bar{c}$)	x ($b\bar{b}$)
Pb+Pb (5.5 TeV)	4.3×10^{-4}	1.6×10^{-3}
pp (14 TeV)	1.7×10^{-4}	6.4×10^{-4}

'High' p_t (6-15 GeV/c)
here energy loss can be studied
(it's the only expected effect)

Charm in-medium quenching (2)

- Quenching for heavy-quarks is expected to be less effective than for light quarks
- Radiative energy loss for massive partons reduced by "dead-cone" effect

  - Heavy quarks with momenta < 20-30 GeV/c $\rightarrow$ v < c
  - Gluons cannot be radiated at angles < m_Q/E_Q (destructive quantum interference)
  - D mesons quenching reduced ("confirmed" at RHIC)



Ratio D/hadrons (or D/π^0) enhanced and sensitive to medium properties

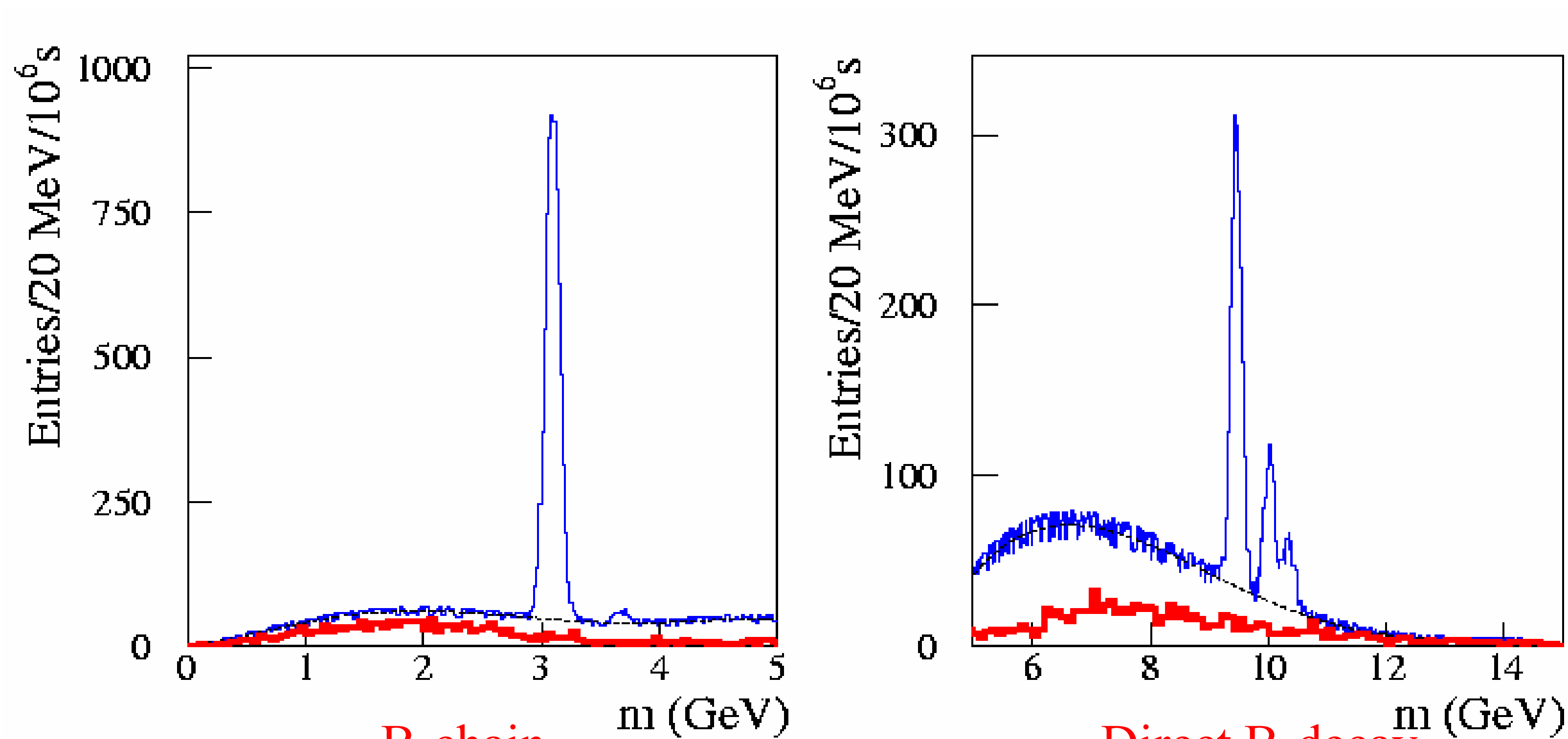
R_{AA} ~ 0.7-0.8 decreasing at high p_t

R_{AA} ~ 0.4-0.5 increasing at high p_t

Open beauty

- Dimuon arm → single muon high p_T cut

$p_T^{cut} = 3$ GeV/c



B-chain

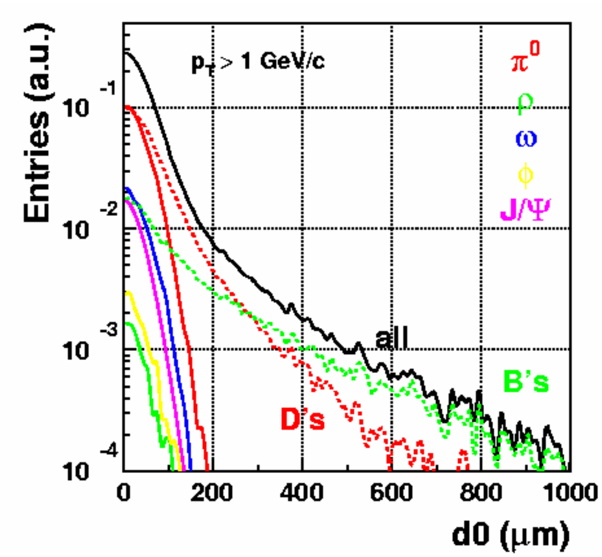
Direct B-decay

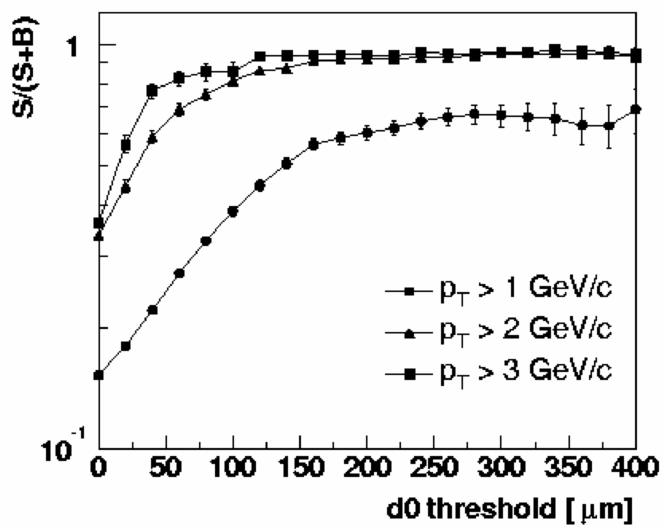
Open beauty (2)

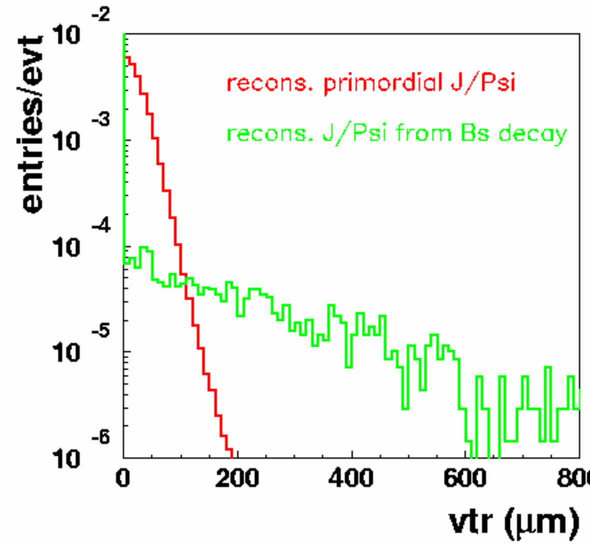
•Central barrel

→ TRD + TPC dE/dx, ITS for vertexing

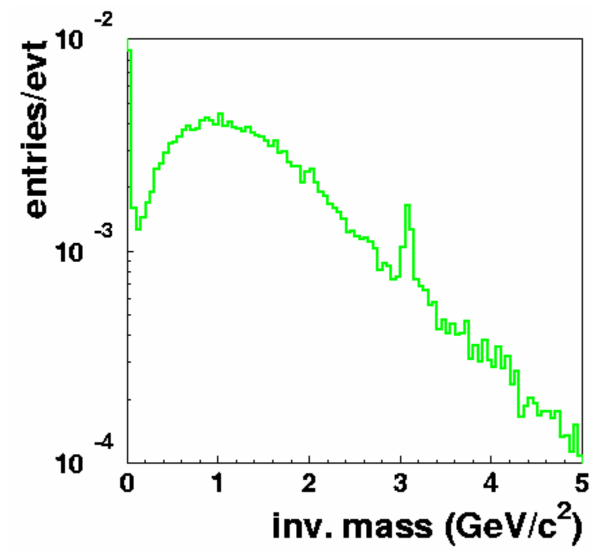
•Single electron with displaced vertex (and high p_T)







Displaced J/ψ vertices



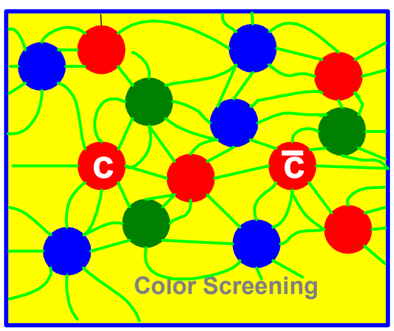
p_T > 2 GeV, d0 > 180 μm → $8\cdot10^4$ B/(ALICE yr)

Quarkonia suppression

$c\bar{c}$ pairs are produced very early in the collision by gluon fusion ⇨ probe the medium they cross

- Confined medium
  - Strongly bound states are not easy to break in the (relatively) soft interactions with comoving hadrons. Anyway they can interact with nuclear matter from target/projectile

    ⇨ Effect to be estimated experimentally



- Deconfined medium
  - The charm quarks are screened in the partonic color field

    ⇨ Successive melting of charmonium states

Binding energy:

$J/\psi \approx 650$ MeV

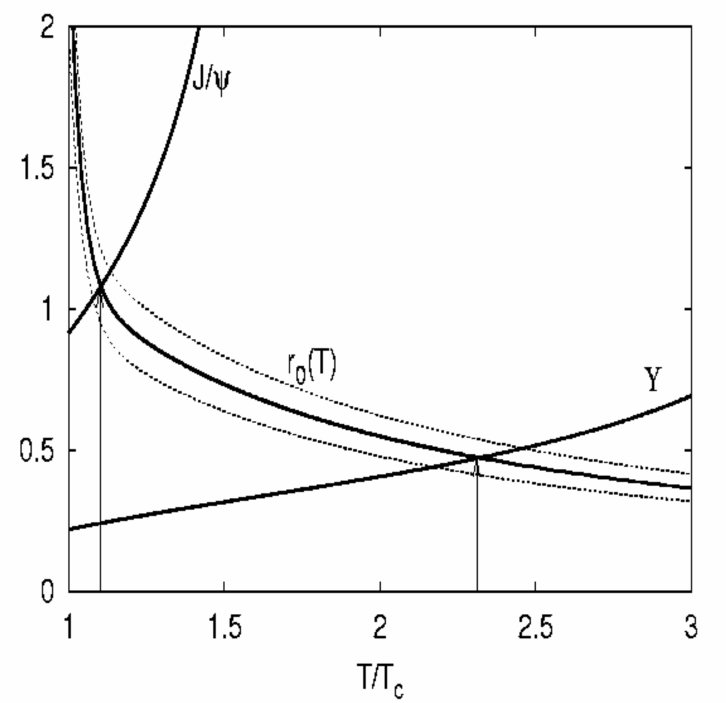
$\chi_c \approx 250$ MeV

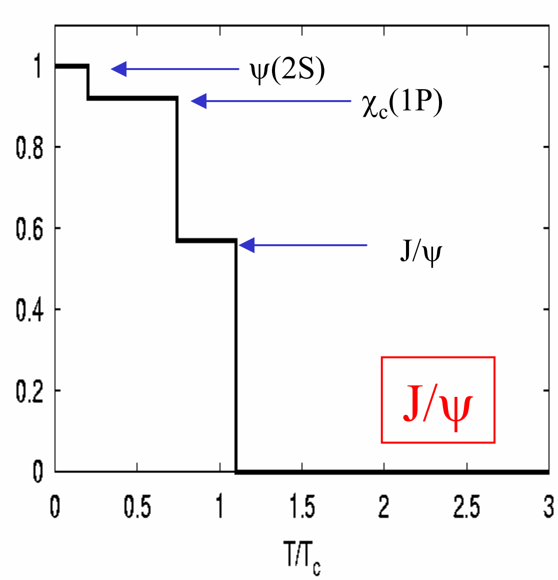
$\psi' \approx 50$ MeV

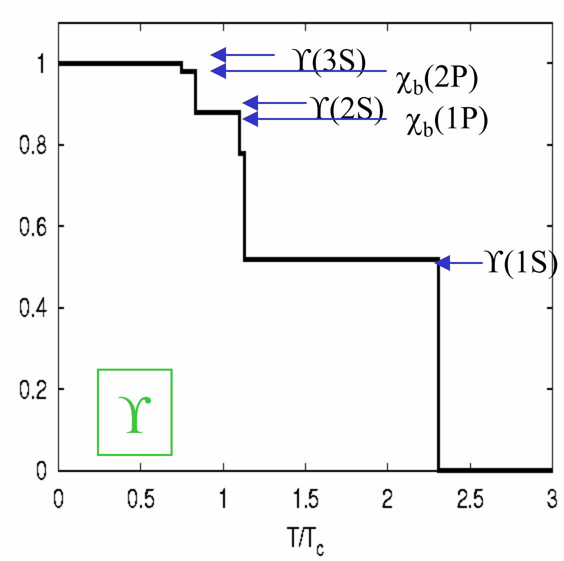
Hierarchy of suppression

Matsui and Satz , Phys. Lett. B178 (1986) 416

Melting of charmonia and bottomonia





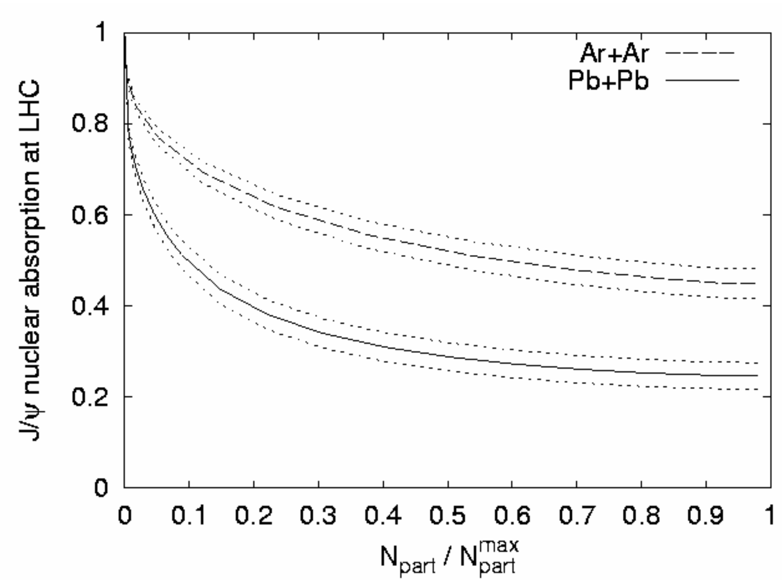


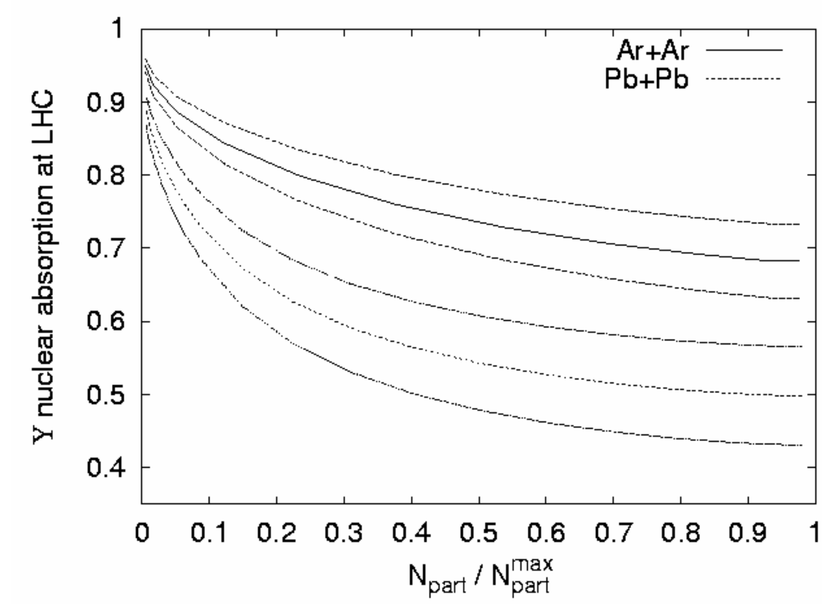
- Radii of quarkonia states increase with T
- ϒ melting only accessible at the LHC

Melting of excited states decaying into J/ψ (ϒ) gives complex suppression patterns

Sensitive thermometer of the QGP

Normal absorption: the baseline



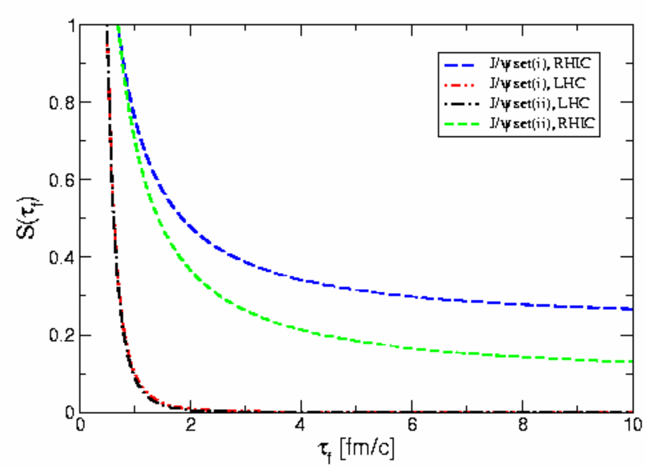


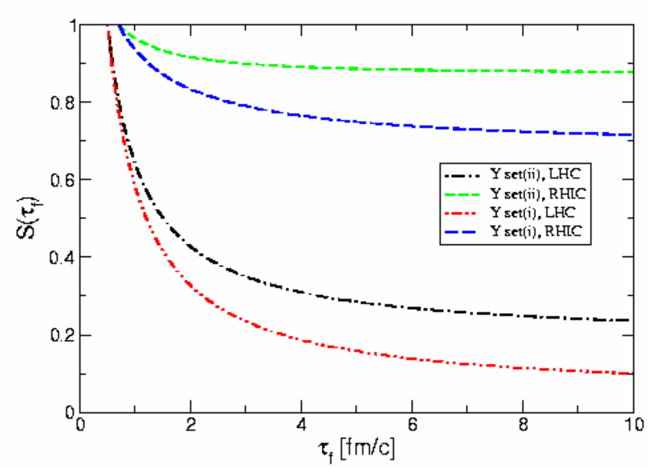
- Reliable predictions exist for nuclear absorption of quarkonia (based on SPS/FNAL energy data)
- Absorption in a hot hadron gas is a much more debated topic
- Possible enhancement due to incoherent recombination mechanisms (~200 c/collision) → Might mask suppression effects for charm (not for beauty)

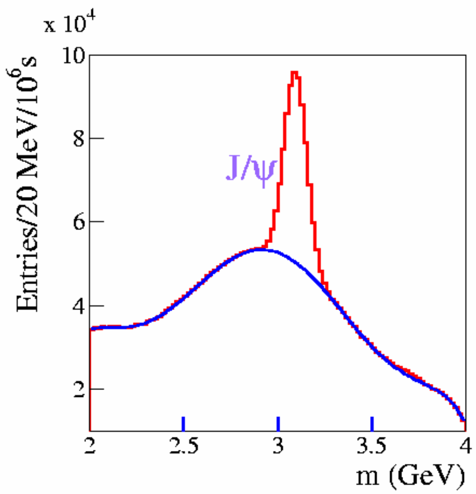
QGP dissociation

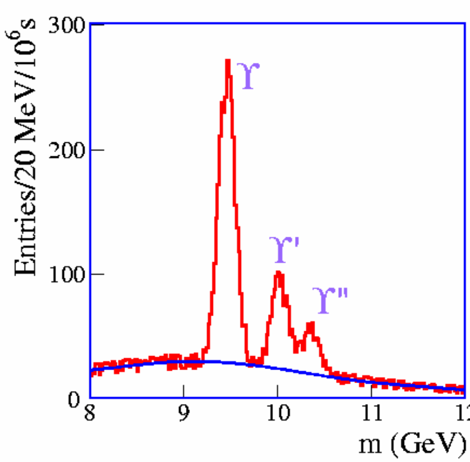
	LHC	RHIC	SPS
T_0 [GeV]	0.72	0.4	0.25
τ_0 [fm/c]	0.5	0.7	1.0

- J/ψ completely suppressed @ LHC energy
- ϒ may provide robust information on QGP initial temperature/lifetime









Expected statistics for 1 ALICE yr

system	state	B ($\times 10^3$)	S ($\times 10^3$)	S/B	$S/\sqrt{S+B}$
Pb+Pb	J/ψ	320	230	0.72	310
	ψ'	150	4.6	0.03	12
	Υ	0.25	1.8	7.1	39
	Υ'	0.22	0.54	2.5	19
	Υ''	0.18	0.26	1.5	12

Conclusions

•Exciting new range of energy yet unexplored in any respect (Close to the cosmic knee)

•SPS, RHIC: study of the phase transition
•LHC: hotter, larger and longer-living QGP phase

Parameter		SPS	RHIC	LHC
$\sqrt{s_{\rm NN}}$	[GeV]	17	200	5500
$\mathrm{d}N_{\rm gluons}/\mathrm{d}y$		$\simeq 450$	$\simeq 1200$	$\simeq 5000$
$\mathrm{d}N_{\rm ch}/\mathrm{d}y$		400	650	$\simeq 3000$
Initial temperature	[MeV]	200	350	> 600
Energy density	[GeV/fm^3]	3	25	120
Freeze-out volume	[fm^3]	few 10^3	few 10^4	few 10^5
Life-time	[fm/c]	< 2	2-4	> 10

$$\alpha_s(T) = \frac{4\pi}{18\,\ln(5\,T/\Lambda_{\rm QCD})} = \begin{cases} 0.43 & \text{for } T = T_c \\ 0.3 & \text{for } T = 2\,T_c \\ 0.23 & \text{for } T = 4\,T_c \end{cases}$$

•Baryon free → can be quantitatively studied with lattice QCD tools
•Approach perturbative regime

•Difficult experimental challenge
•Detectors being built → ready to take first data in 2007 !